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Ion beam and Neutron Output from a Sub-kiloJoule Dense Plasma Focus

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Abstract. We are seeking to gain a better fundamental understanding of the ion beam acceleration and neutron production dense plasma focus (DPF) device. Experiments were performed on a kilojoule level, fast rise time DPF located at LLNL. Ion beam spectra and neutron yield were measured for deuterium pinches. Visible light images of the pinch are used to determine the pinch length. In addition, an RF probe was placed just outside the cathode to measure fluctuations in E_z up to 6 GHz, which is within the range of the lower hybrid frequencies. We find these oscillations arise at a characteristic frequency near 4 GHz during the pinch. Comparisons of the neutron yield and ion beam characteristics are presented. The neutron yield is also compared to scaling laws.

INTRODUCTION

Dense plasma focus (DPF) devices produce high current ion and electron beams which may be useful for accelerator applications, either as an injector or an acceleration stage. Multiple experiments [1,2] report measured deuteron energies >5 MeV on DPFs, including a machine with as little as 5.4 kJ stored energy. Neutrons are produced when the device is operated with deuterium or tritium gas. A better understanding of the beam production in pinch plasmas is necessary to exploit this technology.

Ion beams from DPF plasmas have been measured using magnetic spectrometers with track detectors [2, 3] and from time of flight with Faraday cups [2,4,5,6] or Si PIN detectors [1]. Multiple papers [2, 3, 7] reported that the optimum gas fill pressure for high energy beam production was lower than the optimum fill pressure for maximum neutron production. The DPF scaling law published by Lee and Saw [8] finds that the average ion energy from a DPF is between 25-292 keV and is independent of the device energy, but the beam current scales with the peak current of the device and the beam ion number (ions/kJ) scales with the energy of the device. However, there is little beam data available for sub-kJ operation or fast rise time devices.

Here we report on ion beam measurements and neutron yields from the 1 kJ DPF at LLNL. The LLNL device [9] uses a low-inductance 3.16 μF capacitor bank driver and reaches peak current in just ~400 ns. Fast drivers have been demonstrated to increase yield and therefore might be expected to increase beam energy or total accelerated charge. We present correlations between the ion beam energy and the neutron yield, measurements of E_z fluctuations in the plasma, and compare the neutron yields in this device to published scaling laws.

METHODS

The experiments described in this paper were performed on a Mather type dense plasma focus (DPF) device using deuterium fill gas (1-4 Torr pressure) and a 3.16 μF capacitor bank at operating voltages between 22 kV and 30 kV (0.8 - 1.4 kJ). The device, the neutron diagnostics, the ion beam diagnostic, and the diagnostic calibration details are described in detail in Ref.9. The data shown for the neutron scaling law comparisons and ion beam measurements were collected using a 2 cm diameter copper anode, hollowed out to a depth of 0.6 cm with an inner diameter of 1.3 cm. The RF probe measurements were collected using a 3 cm diameter copper anode with a stainless steel plug in the center. In both configurations, we used 8 copper cathode rods and an anode to cathode spacing of 1 cm. Deuterium gas was injected symmetrically between the rods by gas puff.

Ion beam distribution was measured with time-of-flight method using a 48 cm long flight tube and a Faraday cup with a 0.5 cm diameter aperture. The flight tube has an entrance aperture of 0.1 cm diameter. A grid in front of the Faraday cup collector is biased to -50 VDC to suppress electrons. A magnetic field of 1.2 kG is applied parallel to the grid for additional suppression. The fill gas to the DPF device is puffed so the pressure in the flight tube is remains <8 mTorr at the time of the pinch. The beam travels 17 cm through high pressure gas before entering the flight tube. The beam stopping and charge exchange in the neutral gas is accounted for in the reported beam data.

Neutron yield was measured using an array of 14 ^{3}He tubes in a polyethylene moderator. An additional 4" thick block of polyethylene moderator was placed between the pinch plasma and the ^{3}He detector to prevent pulse pile-up in the detectors and spread the signal out in time. The detector was calibrated in-situ using an ^{241}Am source and MCNP calculations were used to generate the correction factors for DD neutrons and also the efficiencies for time region of interest windows so the neutron yield can be determined using data collected during times when the detector is not saturated. The neutron yields from this detector were compared to the yields from a calibrated neutron activation counter and the measurements agreed to within a factor of two.

The pinch current was measured using a calibrated Current-Viewing Resistor (CVR) diagnostic. The inductance of the resistors in the CVR is non-negligible so the diagnostic measures a combination of I and dI/dt. We solve for I using a differential equation based on the circuit model, and we numerically differentiate I to get dI/dt. This method enhances the noise, but that has been taken into account in computing the error bars.

An RF antenna made from exposing a coaxial cable was placed outside the plasma parallel to one of the cathode rods. Most of the cable was shielded from the plasma by the cathode rod, but the antenna portion was exposed to signals from the plasma to measure E_z, where z is the symmetry axis of the DPF. The signal from this antenna was digitized by a 6 GHz bandwidth oscilloscope to directly measure the high frequency fluctuations in the plasma. A high pass filter with a bandpass of 300 kHz was used to suppress the low frequency noise and attenuators were used to keep the voltage in the range of +/- 0.5V.

RESULTS AND DISCUSSION

Deuteron beam energy > 400 keV has been measured from time-of-flight measurements [9]. We have also observed that the optimum pressure for producing energetic deuteron beams is lower than the optimum pressure for maximum neutron yields in the LLNL device. The ion distribution function is computed from time of flight using the Faraday cup data assuming that all of the beam is D^+. The beam passes through a region of high pressure D_2 gas in the vacuum chamber before entering the flight tube. The beam equilibrium ionization fraction, dictated by both charge-exchange neutralization and subsequent impact ionization, is close to 50% at 100 keV and increases at higher ion energies [10]. This correction factor is applied to the ion distribution function. The total beam energy that was collected is then calculated by numerically integrating the ion beam distribution function over the full range of data.

In FIGURE 1, the ion beam energy is compared to the measured neutron yield for pinches produced using three different charge voltages corresponding to capacitor bank energies of 0.8 kJ, 1.0 kJ, and 1.2 kJ. The peak currents are 130 kA, 145 kA, and 160 kA, respectively. The beam energy increases with increased neutron yield and the relationship is roughly linear over the range of data that were collected. The pinches with higher capacitor bank energies tend to have slightly larger neutron yields, but the general trend of the data is the same for the three charge energies.

The highest measured neutron yields for the LLNL device at 0.8, 1.0, and 1.2 kJ bank energies are $2{\bullet}10^7$, $3{\bullet}10^7$, $5{\bullet}10^7$, respectively. These yields are within a factor of two from scaling $Y_n{\sim}0.1I_{peak}^4$[11]. The neutron yields are also in good agreement with the scaling law devised by Soto *et. al.* [12] for sub-kJ DPFs, $Y{\sim}2.43E^{2.38}$ where E is the capacitor bank energy. In FIGURE 2, we compare the yields in our device to the Bures and Krishnan scaling law, $\frac{Y_n}{l_{pinch}} = \left(\beta\left|\frac{dI}{dt}|_{max}/\ \frac{dI}{dt}|_{min}\right| + \gamma\right) I_{max}^{\delta}$ [8], where Y_n is the neutron yield, l_{pinch} is the pinch length, and β, γ, δ are fitting factors. Typical plasma lengths of 0.6-1 cm have been measured from visible light emission using an ICCD camera in this device [7]. The data also agree with the scaling law to within a factor of two. The points are clustered near the Bures and Krishnan scaling line, but the scaling under-represents the yield for this device for

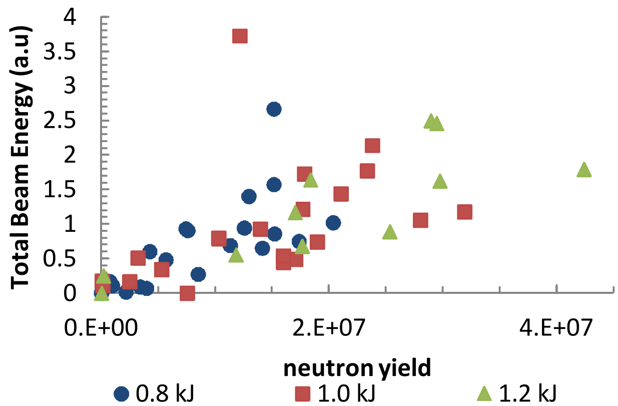

FIGURE 1: The total beam energy along the z-axis, determined by integrating the time of flight data from the Faraday cup, is compared to the total neutron yield measured by a He^3 diagnostic.

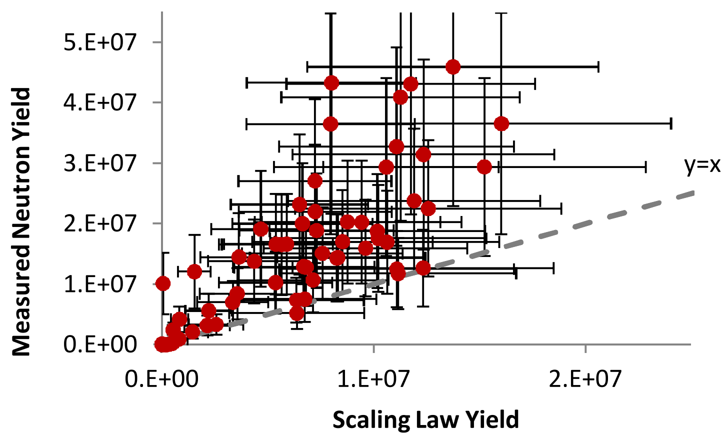

FIGURE 2: Comparison of the measured neutron yields to the predicted neutron yields from the Bures and Krishnan [11] scaling. A characteristic length of 0.6 cm was used for these pinches based on visible light measurements of the plasma.

many of the pinches. The fast rise time driver may be responsible for the enhanced neutron yield relative to the scaling law.

High frequency fluctuations are observed during the pinch on the RF antenna near the time of the pinch. An example is shown in FIGURE 3, including a spectrogram and the raw data. The current traces show more current recovery than expected, which may be an artifact of frequency-dependent inductances that are not included in the current reconstruction. Activity is present in the 1-5 GHz range during the pinch. We have observed these high frequency fluctuations on a number of pinches. The observed frequencies are within the lower hybrid range of frequencies for this experiment. Particle-in-cell simulations of the pinches in this device predict fluctuations in E_z in this same range of frequencies [13].

CONCLUSIONS

We have shown ion beam measurements from a fast rise-time, sub-kJ scale DPF. The ion beam energy is comparable to that measured in similar size devices with slower rise-times [2]. The ion beam energy measured along the z-axis increases linearly with neutron yield. The neutron yields produced in this device are consistent with the published scaling laws for low energy DPF devices [12]. A comparison to the scaling law developed Bures and Krishnan [11] shows that our neutron yields outperform the scaling law for some of the pinches, but are still within a factor of two. Electric field fluctuations were measured by an RF probe. High frequency fluctuations of E_z with

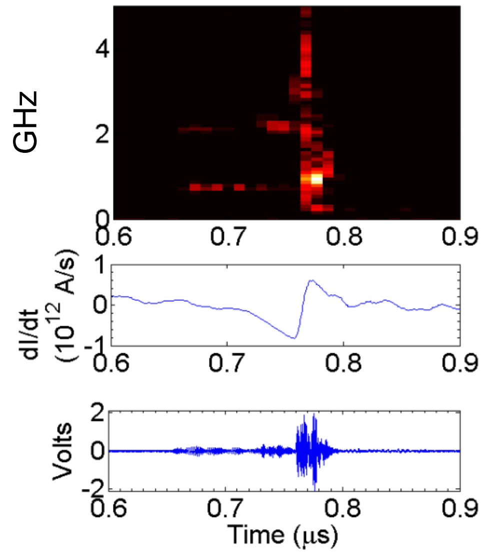

FIGURE 3: High frequency fluctuations in E_z are observed during the pinch. This figured shows the spectrogram, dI/dt, and the raw signal collected from the RF antenna.

in the range of 4 GHz are present in the plasma during the pinch. These fluctuations are within the range of lower hybrid frequencies expected for the magnetic fields in this device.

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